Breakthrough underwater technology holds promise for improved local tsunami warnings

J. Paros¹, E. Bernard², J. Delaney³, C. Meinig², M. Spillane², P. Migliacio¹, L. Tang², W. Chadwick⁴, T. Schaad¹, S. Stalin²

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Piscataway, NJ 08854 USA

¹Paroscientific, Inc., ²NOAA/Pacific Marine Environmental Laboratory, ³University of Washington, ⁴Oregon State University

Abstract

Recent advances in deep-ocean tsunami measurement technology coupled with tsunami forecast models have demonstrated that tsunami impact can be predicted before the tsunami reaches the affected coastlines. Since 2004, tsunami impacts have been predicted for 33 tsunamis detected in the deep-ocean with about 80% accuracy when observations and predictions at tide gauges are compared. In most of these tsunamis, the forecast was based on observations typically 1000km or more from the earthquake epicenter. A remaining challenge is to forecast tsunamis in the near field where the tsunami signal may be overwhelmed by the earthquake vibrations. A new generation of pressure sensors, named nano-resolution pressure sensors, can provide high temporal resolution of the earthquake and tsunami signals without losing precision. The nano-resolution pressure sensor offers a state-of-the-science ability to separate earthquake vibrations and other oceanic noise from tsunami waveforms, paving the way for accurate, early warnings of local tsunamis. This study describes an experiment, begun on June 30, 2010 at the Monterey Accelerated Research System (MARS) cabled observatory in Monterey, California, comparing conventional pressure sensors with the nano-resolution sensor at a depth of approximately 900m. The study will include examples of earthquakes, both local and remote, detected by the nano-resolution pressure sensor since its deployment. Wavelet analysis has been employed to identify two remote micro-tsunamis in late 2010. The events (Dec. 21, M7.4 at Bonin Island; Dec. 25, M7.3 near Vanuatu) produced tsunami signals of 1-2 mm in amplitude in Monterey Bay at periods near 14 minutes.

I. INTRODUCTION

Deep water (up to 6000 meters) distant tsunami detection capability has been demonstrated by the NOAA-led U.S. National Tsunami Hazard Mitigation Program. [1]-[5] A goal of the program is to increase the accuracy and reliability of tsunami warnings and to quickly confirm potentially destructive tsunamis or, more commonly, eliminate unnecessary evacuations. A network of sensors throughout the Pacific and Atlantic has been highly reliable and the real-time data stream has proven its value to warning center decision-makers during a number of potentially dangerous tsunamigenic events. One of the remaining challenges is to forecast tsunamis in the near field where the tsunami signal may be obscured by earthquake vibrations and other ocean “noise” not commonly found at deep water installations.

Inherently digital quartz resonator sensors (developed and manufactured by Paroscientific, Inc., Quartz Sensors, Inc., and Quartz Seismic Sensors, Inc.) utilize resonators that change frequency under load. The measurand-induced loads are generated by pressure, acceleration, gravity, weight, etc., depending on the sensor type. New nano-resolution pressure sensors have been developed that are able to provide the temporal resolution required to distinguish between earthquake, ocean “noise” and tsunami frequencies without losing precision. New improved counting techniques can measure the frequency outputs of the quartz resonator sensors to parts-per-billion precision (nano-resolution). For an overview of nano-resolution please see: http://paroscientific.com/Nano-Resolution.pdf. All measurements taken in this paper use nano-resolution counting with multi-stage digital IIR low pass filters [6].

An opportunity to test a nano-resolution sensor, in the ocean environment, was presented by a geophysical instrument package that was already funded by the National Science Foundation (NSF) and under development by Oregon State University (OSU) and National Oceanic and Atmospheric
Administration (NOAA)/Pacific Marine Environmental Laboratory (PMEL). The original OSU/PMEL instrument was designed for submarine volcano monitoring and included high- and low-resolution tilt sensors and a standard bottom pressure recorder (BPR) for detecting vertical displacements of the seafloor due to volcanic inflation/deflation [7]. Part of this project was to test the instrument for a year on the Monterey Accelerated Research System (MARS) cabled observatory, located in Monterey Bay, California, and operated by the Monterey Bay Aquarium Research Institute (MBARI). MARS is a test bed for instrumentation that could be used by NSF’s Ocean Observatories Initiative (OOI) (http://www.mbari.org/mars/general/about_mars.html). Fig. 1 illustrates the location of the MARS test bed. The OSU/PMEL instrument was designed to be eventually deployed at Axial Seamount, an active submarine volcano that will be a node on the cabled observatory component of the OOI in the NE Pacific (http://www.interactiveoceans.washington.edu/stor y/Regional+Scale+Nodes).

During the development of the OSU/PMEL instrument, a nano-resolution pressure sensor was added, through a collaboration of NOAA/PMEL, University of Washington, and Paroscientific, Inc., in a joint effort to demonstrate the capability of forecasting tsunamis in the near field using this new technology. The OSU/PMEL instrument package was deployed on the MARS cable on June 30, 2010 at a depth of approximately 900 m, and data from the sensors are displayed in near-real time on-line: http://www.pmel.noaa.gov/vents/geology/mars/. The experiment and analysis is ongoing (until June 28, 2011) and compares a standard NOAA BPR (Bottom Pressure Recorder) (http://nctr.pmel.noaa.gov/Dart/Pdf/DARTII_Des cription 6 4 05.pdf) to the nano-resolution pressure sensor. Both sensors are installed on the same tripod platform as shown in Fig. 2.

II. DATA FROM THE MONTEREY ACCELERATED RESEARCH SYSTEM (MARS) EXPERIMENT

The new nano-resolution pressure sensor manufactured by Paroscientific, Inc. has several orders of magnitude higher resolution than a traditional sensor installed in a NOAA BPR. It is also capable of recording data at much higher sampling rates. This unprecedented resolution allows scientists to better distinguish between oceanographic signals/noise and seismic events for improved tsunami detection and modeling. The nano-resolution pressure sensors are able to measure ocean signals with unprecedented clarity, including the detection of microseisms, infragravity waves and earthquakes. The plot in Fig. 3 compares the standard NOAA BPR to a nano-resolution pressure sensor. The nano-resolution pressure sensor is able to distinguish pressure changes equivalent to a fraction of a millimeter that are the result of microseisms and longer-period infragravity waves.

The nano-resolution pressure sensor can be configured through software commands to change the measurement parameters and it is co-located with a standard resolution NOAA BPR to enable comparative measurements between the two. A collaborative analysis effort between NOAA, UW, Paroscientific, Inc. and others in the Regional Cabled Network Community is ongoing to examine, analyze, compare and correlate the pressure data with nearby seismometers, tilt, and tide gauge information. To date, this experiment has shown that sea floor measurements of absolute water levels, tides, infra-gravity waves, microseisms and signals from distant and nearby earthquakes can be made with greater accuracy than with previous instrumentation.
Earthquakes can produce dynamic pressure variations, which are infrasonic acoustic waves. These waves, produced by earthquakes with magnitudes as low as 3.0, have been detected by the nano-resolution pressure sensor at MARS. At longer periods, the entire water column above the sensor moves up and down in response to the passing tsunami wave train with an amplitude that can be computed from the sea floor pressure fluctuations with the scaling \( P = \rho g h \) (water density, gravity, and height). Accurate time series of a tsunami signal, for comparison with pre-computed model scenarios, are the basis of the forecast system\([2]\). The high-frequency earthquake signal is noise for the tsunami detection process. With standard sensors, this noise overwhelms the tsunami signal making tsunami detection difficult. The improved temporal sampling and vertical accuracy provided by nano-resolution pressure sensors shows promise for tracking the earthquake vibrations while recording the tsunami signal, opening the possibility of near field tsunami detection. At NOAA/PMEL, L. Tang and E. Tolkova are investigating spectral techniques to achieve this decoupling, both in the cabled data stream and by in-situ signal processing for future generations of the DART buoy system.

The nano-resolution pressure sensor used in the test has a full scale range of 1400 meters of water. The sensor ambient noise is about -180 dB (in the time-domain near 1 Hz) equivalent to a few microns of water level. The nominal sampling rate of the sensor is 40 Hz, but can be changed in real-time. The actual data rate can be inferred by dividing the difference of the nearest hourly time-stamps by the number of samples. From that we also determined the actual GPS time for each sample. The data was taken in the IIR nano-resolution mode with 5 low-pass filters. The frequency cutoff was initially set at 0.7 Hz (software parameter IA=11). Spectral analysis of these data, as shown in Fig. 4, shows the wide range of earth dynamics, from infragravity ocean waves to micro-seismic ground motion, measured by the nano-resolution pressure sensor. On 7/20/2010, approximately 20 days after deployment, the frequency cutoff was changed to 5.5 Hz (IA=8) to explore the background at higher frequencies. This makes observations of p-waves for moderately strong earthquakes possible.

III. LOCAL AND DISTANT EARTHQUAKE DETECTION

Three data files were analyzed for distant and local earthquake activity: 1) at the start on 6/30/2010 from 1900 – 2100 UTC, 2) on 7/10/2010 1000-1300 UTC and 3) on 7/21/2010 0600 UTC when the data filter was changed from 1 to 5 Hz. Earthquake locations are shown in Fig. 5.

A. Distant Earthquake Detection: M6.2 Mariana Island Earthquake

The 7/10/2010 file (see plot in Fig. 6) was used to search for earthquake waves from the M6.2 EQ in the Mariana Islands on 7/10/2010 originating at 11:43:32 UTC.
B. Local Earthquakes
   i) M5.4 Palm Springs Earthquake
      Preliminary data from the M5.4 EQ near Palm Springs on 7/7/2010 at 23:53:33 UTC was also analyzed (see plots in Fig. 7). The arrival of the p-waves from this earthquake coincided with seismic data from the nearest land-based station at San Juan Grade (see Fig. 8). The largest amplitudes were equivalent to +/- 8 mm water height (however, it would have been larger with a higher low-pass filter cutoff in the counting algorithm).

   ii) M3.4 Central California Earthquake
      Data from the 7/21/2010 file contains data filtered from 1 to 5 Hz. The data matches the results from the UC Santa Cruz station very well. At these higher frequencies, the pressure sensor does not see the ocean waves, but senses ground motion. The earthquake had a magnitude of M3.4 and was located in Central California at 7/21/2010 6:54:36 UTC (see plots in Fig. 9). The peak pressure in the band-pass 1 to 5 Hz was 33 Pa (Pascal). Seismic and pressure data will be compared and we expect that the infra-gravity waves measured by the nano-resolution pressure sensor can be used to improve the signal-to-noise ratio of nearby seismometers in the long-period domain.

IV. DISTANT TSUNAMI DETECTION

Two micro-tsunamis were recorded by the nano-resolution pressure sensor on December 21, 2010 (M7.4 Bonin Island earthquake) and December 25, 2010 (M7.3 Vanuatu earthquake). Using wavelet analysis, spectrograms were computed for each tsunami (see plots in Figs. 10 and 11 below). For each analysis, the cutoff period for tide removal is 1 hour, using Butterworth filters. Note the color scale in the plot was set to emphasize the tsunami, so the high frequency components are muted. The red line in the upper panel is the modeled tsunami amplitude time series. In Fig. 10, for the Bonin Island event, the tsunami appears from 645-745 minutes (indicated by white dashed line) with period of about 14 minutes; the maximum tsunami amplitude is about 0.2 cm. In Fig. 11, for the Vanuatu tsunami, the tsunami appears from 765-840 minutes (indicated by white dashed line) with period of about 14 minutes. Maximum tsunami amplitude is about 0.1 cm.
Figure 5. Location of earthquakes discussed in this report relative to the location of MARS observatory.

Figure 6: Both NOAA and Paroscientific are creating viewfinders to make it easier to sort through the data. The one shown above is an hourly segment on 7/10/2010 after 11 UTC. The band-pass is 1 to 2 Hz, technically above the frequency cutoff of 0.7 Hz of the counter; however, micro-seismic fluctuations at 0.2 Hz are still clearly visible. The disturbance at the bottom at 11:56 UTC is tentatively identified as the p-waves from a distant earthquake, the M6.2 earthquake at Mariana Islands on 7/10/2010 11:43:43 UTC.
Figure 7: A sample of the NOAA viewfinder (detided by removing a linear trend from each 10-minute segment). Again, the dominant background signals are microseisms near 0.2 Hz and longer-period surface waves (or infra-gravity waves). The pressure measurement of the July 7, 2010 earthquake is shown in the lower right-hand corner and compared to the seismometer in Figure 8.
Figure 8: The upper panel shows consecutive 15-minute segments of the nano data (detrended) that correspond to the similarly colored traces in the USGS record from San Juan Grade in the lower panel. Inset is a locator map for the two locations which are separated by about 56 km. Vertical lines in red show the earthquake time and the arrival at the seismometer. The Nano-resolution pressure sensor begins to respond a couple of minutes later and its earthquake signal has a similar duration to the land-based instrument.

Figure 9: 7/21/2010 0600 UTC data filtered from 1 to 5 Hz. This was an M3.4 EQ in Central California at 7/21/2010 6:54:36 UTC. The pressure data matches the results from the UC Santa Cruz seismic station very well. At these faster frequencies, the pressure sensor does not see the ocean waves, but senses dynamic pressure variations (acoustic waves) created by ground motion. The peak pressure in the band-pass 1 to 5 Hz was 33 Pa (Pascal). The IA=8 setting with the 5.5 Hz corner frequency works well to see smaller local earthquakes.
Figure 10: A micro tsunami generated by the M7.4 Bonin Island Earthquake on December 21st, 2010 was recorded by the Nano sensor. (a) The black line is the Nano observations with tides removed by a Butterworth filter with a cutoff period of 1 hour. The red line is the modeled tsunami amplitude time series. (b) Wavelet-derived amplitude spectrogram of the observations. The white dashed line indicates the existence of the tsunami signals.

Figure 11: A micro tsunami generated by the M7.4 Vanuatu Earthquake on December 25 was recorded by the Nano sensor. (a) The black line is the Nano observations with tides removed by a Butterworth filter with a cutoff period of 1 hour. The red line is the modeled tsunami amplitude time series. (b) Wavelet-derived amplitude spectrogram of the observations. The white dashed line indicates the existence of the tsunami signals.

V. SUMMARY AND CONCLUSIONS

Nano-resolution pressure sensors have been developed with the capability to measure pressure changes with unprecedented precision over an extended frequency spectrum. Tests at the MARS Cabled Observatory have demonstrated the ability to discriminate between high resolution pressure signals induced by microseisms, infragravity waves, earthquakes, and micro-tsunamis. These developments hold promise for improving local tsunami forecasts by making possible earlier detection close to the source.
REFERENCES


